

PROPERTIES OF GALLIUM ARSENIDE DIODE LASERS

1. Interference Effects in the Far-Field Patterns of Semiconductor Diode Lasers
2. Gallium Arsenide Diode Lasers with Oblique Angles Between the Resonator Mirrors and the p-n Junction
3. Observation of Mode Coupling in GaAs Lasers

INAUGURALDISSERTATION
der
philosophisch-naturwissenschaftlichen Fakultät der
Universität Bern
zur Erlangung der Doktorwürde

vorgelegt von
Christian Deutsch
von Itingen (BL)

Von der philosophisch-naturwissenschaftlichen Fakultät auf Antrag von
Herrn Prof. Dr. K.P. Meyer angenommen

Bern, den 14. Dezember 1967

Der Dekan: Prof. Dr. M. Lüscher

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INTERFERENCE EFFECTS IN THE FAR-FIELD PATTERNS
OF SEMICONDUCTOR DIODE LASERS

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Part of the far-field interference pattern of GaAs-lasers is shown to be caused by light diffracted from the back mirror and transmitted through the n-region. The effect can be eliminated by roughening the n-type side of the front mirror.

Most of the published far-field patterns of GaAs laser diodes show, towards the n-region, a series of lines parallel to the p-n junction [1-3] (fig. 1a). This structure badly disturbs the evaluation of the far-field pattern. The effect is generally attributed to reflections from the mount, and often this is certainly the case. However we have observed that even when all reflections from the mount are carefully eliminated the system of lines persists, always lying on the n-type side even if the diodes are mounted with the p-type side towards the mount. Clearly the source of this pattern must lie within the diode itself. We wish to report that we have found an explanation for the effect based on the results of the following experiments.

Our lasers are of the usual type, Zn-diffused with two cleaved sides and a length of about $300\text{ }\mu\text{m}$. They are operating at 77°K .

Observation of the near-field pattern at an angle of several degrees from the normal to the Fabry Perot cavity, towards the n-type side, shows a second row of laser "spots" of the n-type region at about $20\text{ }\mu\text{m}$ from the p-n junction (fig. 1b). The resolution of an image converter is insufficient to allow exact location of the beam in the n-type region but direct examination of GaAs $1-x\text{P}_x$ diodes through a stereoscopic microscope showed clearly that the light originates from the near-field pattern on the opposite mirror, visible through the n-type region because of the small absorption coefficient (10 cm^{-1}) of the

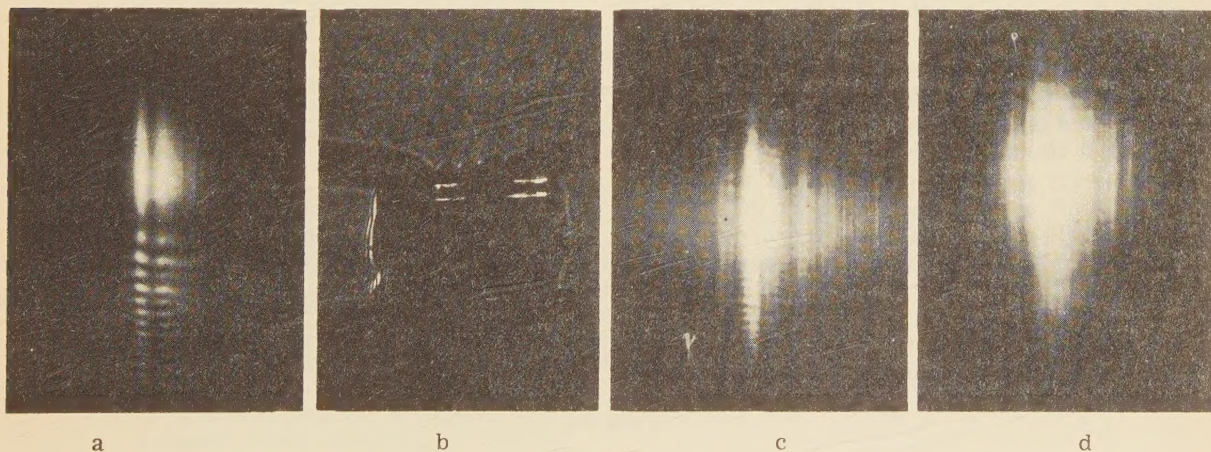


Fig. 1. Near and far-field patterns of GaAs lasers. The p-type region is uppermost in each case. (a) Far-field pattern showing interference lines on the n-type side. (b) Near-field photographed at 10° from the normal towards the n-type side. (c) Far-field pattern of the same diode as in fig. 1(a) with front mirror roughened to within $2\text{ }\mu\text{m}$ of the junction. (d) Far-field pattern of another diode with front mirror roughened to within $4\text{ }\mu\text{m}$ of the junction.

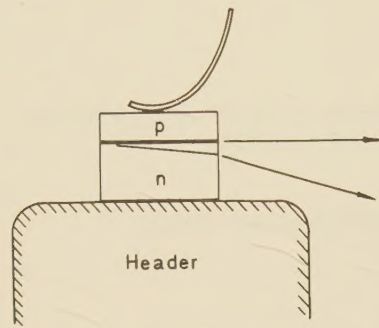


Fig.2. Paths of the two beams in the diode causing interference in the far-field pattern.

latter for the wavelength of the stimulated emission (fig. 2). Assuming that the lines in the far-field pattern are formed by interference of this second source with the main beam, the n-type side of the front mirror was removed to within a few microns of the junction using a wire saw so that light in this area could only be emitted diffusely and would therefore be unable to cause interference effects. It is essential, however, that the edge produced by the wire saw is not too near to the junction, otherwise diffraction effects can introduce new perturbations.

Figs. 1(a) and (b) show the far and near field patterns of a laser before removing part of the mirror, the latter being obtained by photographing at an angle of 10° from the normal to the mirror, towards the n-type side. The lower emission line in fig. 1(b) originates from the back surface of the diode. The almost complete elimination of the horizontal pattern by sawing to within $2\mu\text{m}$ of the junction, for the same diode, is shown in fig. 1(c). Fig. 1(d) shows the far-field pattern of another diode having the front surface roughened to within $4\mu\text{m}$ of the junction. Figs. 3(a) and (b) show densitometer traces of fig. 1(a) and 1(c) respectively.

In summary we like to conclude that at least for diodes with a narrow active region the stripes in the far-field pattern must be attributed to reflected light in the diode and are not due to higher modes.

The author is indebted to R. F. Broom, K. P. Meyer and A. C. Scott for many helpful discussions.

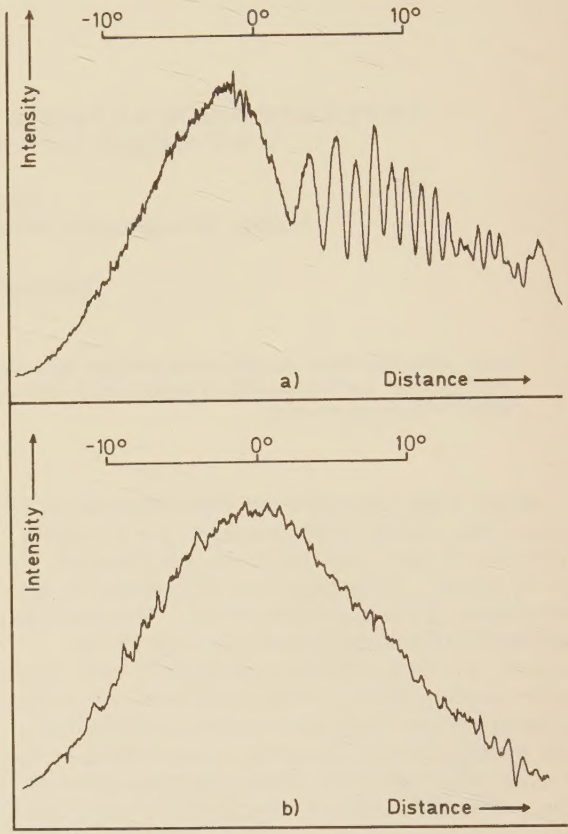


Fig.3(a). Densitometer trace along a vertical line of fig. 1(a). (b) A similar trace of fig. 1(c).

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GALLIUM ARSENIDE DIODE LASERS WITH OBLIQUE ANGLES BETWEEN THE RESONATOR MIRRORS AND THE p - n JUNCTION

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Abstract—Diode lasers have been fabricated in which the junction plane is tilted at angles of $\theta = 0.5$ – 4.5° , in steps of 0.5° , from the normal position at 90° to the cleaved (110) planes forming the Fabry-Perot cavity mirrors. The threshold current as a function of angle has been measured at temperatures of 4.2° , 77° and 195°K . The results are qualitatively similar for all three temperatures; at $\theta = 1.5^\circ$ the threshold current $j = 2j(0)$ and at $\theta = 3.5^\circ$, $j = 8j(0)$. A theory, based on the electromagnetic field variation within the active region, is derived to describe the effective reflectivity of the cavity and hence to calculate the variation of threshold current with angle. Good agreement between experiment and theory is obtained for small angles, up to 3.5° . Above this value theory and experiment diverge and the threshold current rises very rapidly. Reasons for this behaviour are discussed.

Observation of the far-field pattern indicated only axial modes in a plane perpendicular to the junction plane for all values of θ , in contrast to the predictions of geometrical optics.

Finally the results have been used to estimate the accuracy of junction and mirror orientation necessary for InAs and $\text{GaAs}_{1-x}\text{P}_x$ lasers, leading to values of 7° and 0.5° respectively.

Résumé—Des diodes laser ont été fabriquées avec le plan de jonction incliné à des angles de $\theta = 0,5$ – $4,5^\circ$ à étapes de $0,5^\circ$ de la position normale à 90° aux plans clivés (110) formant les miroirs de cavité Fabry-Perrot. Le courant de seuil en fonction de l'angle a été mesuré à des températures de $4,2$, 77 et 195°K . Ces résultats sont qualitativement semblables aux trois températures; à $\theta = 1,5^\circ$ le courant de seuil $j = 2j(0)$ et à $\theta = 3,5^\circ$, $j = 8j(0)$. Une théorie basée sur la variation du champ électromagnétique dans la région active est dérivée pour décrire le réfléchissement effectif de la cavité et aussi calculer la variation du courant de seuil avec l'angle. Un bon accord entre l'expérience et la théorie est obtenu pour les petits angles jusqu'à $3,5^\circ$. Au-dessus de cette valeur la théorie et l'expérience ne s'accorde plus et le courant de seuil augmente très rapidement. Les raisons pour ce comportement sont discutées.

L'observation du schéma à champ distant indiquait seulement des modes axiaux dans un plan perpendiculaire au plan de la jonction pour toutes les valeurs de θ , contrastant aux prédictions de l'optique géométrique.

Finalement les résultats ont été employés pour estimer l'exactitude de l'orientation de la jonction et des miroirs nécessaire aux lasers en AsIn et en $\text{As}_2\text{P}_{1-x}\text{Ga}_x$, menant aux valeurs de 7° et $0,5^\circ$ respectivement.

Zusammenfassung—Es wurden die Eigenschaften von Diodenlasern untersucht, deren p - n -Uebergang gegenüber der normalen Lage senkrecht zu den Spaltflächen, welche die Spiegel des Fabry-Perot Resonators bilden, um $\theta = 0,5$ – $4,5^\circ$ geneigt ist. Die Schwellstromdichte wurde bei $4,2$, 77 und 195°K als Funktion des Winkels gemessen. Die Resultate sind qualitativ für alle drei Temperaturen gleich; bei $\theta = 1,5^\circ$ wird die Schwelle $j = 2j(0)$ und bei $\theta = 3,5^\circ$ ist $j = 8j(0)$. Basierend auf der elektromagnetischen Feldverteilung innerhalb der aktiven Zone wird eine Theorie entwickelt zur Beschreibung des effektiven Reflexionskoeffizienten der Kavität, welche es erlaubt, die Abhängigkeit der Schwelle vom Winkel zu berechnen. Für kleine Winkel, bis $3,5^\circ$, besteht eine gute Uebereinstimmung zwischen Theorie und Experiment. Oberhalb dieses Winkels divergieren Experiment und Theorie und die Schwelle steigt sehr stark an. Gründe für dieses Verhalten werden diskutiert.

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Fernfelduntersuchungen zeigten ausschliesslich axiale Modes in der Ebene senkrecht zur Ebene des p - n -Uebergangs für alle Werte von θ , im Gegensatz zu Voraussagen auf Grund der geometrischen Optik.

Die Resultate wurden verwendet zur Abschätzung der notwendigen Orientierungsgenauigkeit zwischen der Ebene des p - n -Uebergangs und den Spiegelflächen für InAs—und GaAs_xP_{1-x}-Laser, für welche Werte von 7° respektive 0.5° erhalten wurden.

1. INTRODUCTION

THE OPTICAL cavity of a diode laser is generally formed by cleaving in (110) planes. It is necessary for the p - n junction to be in a plane perpendicular to these two mirrors and this is generally achieved by diffusion into a mechanically polished plane which is intended to be (100). Consequently the orientation of this plane in the original slice of material determines the orthogonality of the junction and mirrors. Little information is at present available on the effect of misorientation of the slice on threshold current and mode patterns, and it is therefore of interest to know how these factors are related.

The object of this work was twofold: first to determine as accurately as possible the variation of threshold current for small deviations from the perpendicular, of the angle between mirrors and junction plane, second to determine whether this deviation was capable of exciting off-axis modes in a plane perpendicular to the junction. STERN⁽¹⁾ has shown that such higher order modes could arise and by analogy with the reflection of microwaves at a dielectric wedge⁽²⁾ these modes would appear to be more likely to occur when the angle between mirror and junction differs from 90° .⁽³⁾

In the following work, Section 2 presents a theory for the threshold current as a function of small deviations (θ) from 90° of the angle between junction and mirrors, based on the electromagnetic field distribution in the active region of the diode. Sections 3 and 4 describe the experimental arrangement and the results of measurements on a series of about 50 diodes for values of θ between 0° and 4.5° . The discussion of Section 5 compares these results with theory. Details of the calculation of the internal electric field distribution are given in the Appendix.

2. THEORY

(a) General considerations

A rigorous theory for the threshold current as a function of the angle between the active region

and the mirrors involves considerable difficulties. Maxwell's equations would have to be solved subject to the variation of the complex dielectric constant perpendicular to the junction and to boundary conditions at the tilted mirrors. As the variation of the dielectric constant is not known exactly even a rigorous theory could not be expected to give precise numerical results. Therefore, to simplify the problem, the angular distribution of the reflected light for rectangular diodes is calculated at intrinsic threshold and the effect of tilted mirrors is taken into account by a rotation of this distribution, leading to an effective reflection coefficient for the light returning into the active region (Fig. 1).

As the angle between the cleaved mirror and the junction plane becomes greater or less than 90° the reflected intensity in the direction of the active region decreases. This may be regarded as a decrease in the effective reflectivity for axial modes. A knowledge of this value allows the threshold current to be calculated from the relation,⁽⁴⁾

$$j_{th} = c \left(\alpha - \frac{1}{L} \ln R_0 R' \right) \quad (1)$$

where c is a constant for a given type of junction and a fixed temperature, α is the sum of the absorption losses, typically 10 cm^{-1} ,⁽⁵⁾ L the diode length, R_0 the reflectivity of the mirrors for normal incidence ($R_0 = 0.32$ for cleaved GaAs surfaces) and R' a correction factor accounting for the decrease in reflectivity due to the tilted mirrors. Figures 1(a) and 1(b) show a section of a rectangular and an oblique diode respectively, and the dashed lines indicate schematically the polar diagram of the reflected and transmitted light. The problem is now to calculate the reflected light amplitude distribution, including its phase, and thus to determine R' as a function of θ .

(b) Light amplitude distribution for rectangular diodes

The complex light amplitude at intrinsic

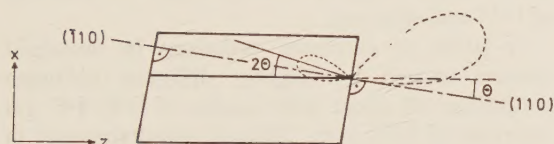
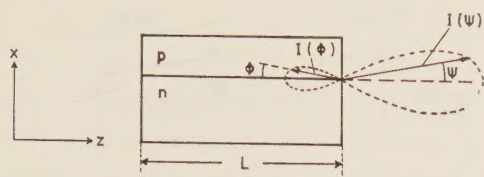


FIG. 1. Section of diode showing the distribution of reflected and transmitted light intensities $I(\phi)$ and $I(\psi)$ respectively. (a) Diode with normal mirrors. (b) Diode with mirrors tilted by an angle θ .

threshold in a direction perpendicular to the junction has been calculated by HATZ and MOHN⁽⁶⁾ on the basis of a triangular shaped variation of dielectric constant and conductivity across the active region normal to the junction. Using this field distribution the light amplitude in the far-field $U(\psi)$ may be found by decomposition of the amplitude $u(x)$ into 'plane' waves with different directions of propagation,

$$U(\psi) = \int_{-\infty}^{\infty} u(x) \exp(ik_0 x \sin \psi) dx \quad (2)$$

$$k_0 = \frac{2\pi}{\lambda}$$

where x is in a direction normal to the junction and ψ is measured from the normal to the mirror, as shown in Fig. 1(a). Note that $u(x)$ may be identified as the nearfield amplitude distribution, and $U(\psi)$ as the farfield amplitude distribution. The integration limits should be taken at the boundaries of the mirror but as the u -function decays very rapidly with distance from the active region it is possible to integrate from $-\infty$ to $+\infty$. The intensity is then given by $UU^*(\psi)$. Equation (2) also gives the normalized angular distribution of

the light reflected back into the diode $U(\phi)$ if k_0 is replaced by $k_0 \cdot n$, where n is the refractive index of GaAs, namely 3.6. This means simply that the angle scale has to be expanded by the relation,

$$\sin \phi = \frac{1}{n} \sin \psi. \quad (3)$$

Figure 2 shows the intensity distribution

$$I = UU^* \quad (4)$$

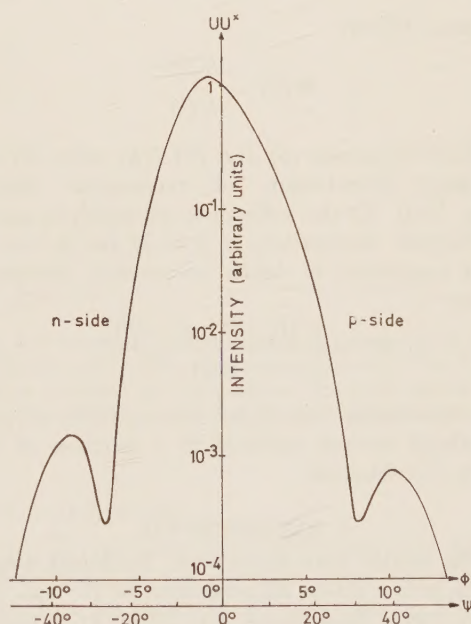


FIG. 2. Calculated farfield pattern $UU^*(\psi)$ and internal angular light distribution, $UU^*(\phi)$.

with both the external and internal angle scales. Details of the calculation are given in the Appendix. Due to the asymmetric distribution of the dielectric constant and the gain coefficient on either side of the junction the calculated intensity distribution is correspondingly slightly asymmetric, both as a function of the spatial coordinate x and of the angular coordinate ψ or ϕ .

The upper part of the calculated farfield distribution is in good agreement with experimentally observed patterns. Details of the lower part are difficult to verify because of the very low intensity and the disturbance caused by scattered light.

(c) *Light amplitude distribution for oblique-angled diodes*

By analogy with the diffraction theory for a slit at oblique incidence, the diffraction pattern of the light reflected back from a mirror tilted by an angle θ is rotated with respect to the incident direction by an amount 2θ [Fig. 1(b)]. The intensity reflected back into the junction plane (I_j) for the oblique diodes is therefore given by,

$$I_j = I(\phi)|_{\phi=2\theta}. \quad (5)$$

Hence it follows

$$R'(\theta) = \frac{I(2\theta)}{I(0)}. \quad (6)$$

In both equations (5) and (6) $I(\phi)$ refers to the intensity distribution of rectangular diodes [Fig. 1(a)]. As the reflections of multiple passes correspond alternatively to $\phi = 2\theta$ and $\phi = -2\theta$ it is reasonable to define an average correction factor,

$$R' = \frac{\sqrt{[I(+2\theta) \cdot I(-2\theta)]}}{I(0)}. \quad (7)$$

By introducing this factor into equation (1) the threshold current variation as a function of the angle θ is obtained.

3. EXPERIMENTAL

The diodes were made from Te-doped *n*-type GaAs with a donor concentration of 10^{18} cm^{-3} .^{*} They were Zn-diffused for 2.5 hr in a quartz ampoule at 850°C with a source of 1 mg $\text{ZnAs}_2 + 2.5 \text{ mg As}$ per cm^3 , resulting in a junction depth of 20 μm . Average dimensions of the diodes were 300 μm in length and 250 μm in width. The mirrors were cleaved and the sides cut with a wire-saw.

Figure 3 shows the arrangement used for orienting the mirrors at the desired angle to the *p-n* junction. It is similar to the one described by PROBSTING.⁽⁷⁾ The slice was mounted on a moveable polishing jig, the polishing plane of which is determined by the tips of three screws. One edge of the slice was cleaved and the beam of a gas-laser reflected from this surface fell on a

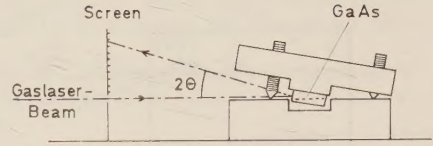


FIG. 3. Orientation jig used for producing oblique mirrors.

screen with a direct scale of the angle θ . The screws could be adjusted to give the desired angle and to define the plane of the junction. An accuracy of 0.1° was obtained.

In order to eliminate variations in threshold current caused by slightly different diffusion conditions all slices with angles of 0.5° – 4.5° (at intervals of 0.5°) were diffused simultaneously in the same ampoule.

In spite of these precautions and identical mounting procedures for all diodes there was still considerable scatter in the thresholds, probably caused by inhomogeneities such as non-uniform background doping, the effects of dislocations, and cleavage steps. However the large number of diodes permitted a reasonable statistical average to be obtained for each angle.

For threshold measurement the diodes were immersed in liquid nitrogen. They were operated with current pulses of 2 μsec length and a pulse repetition frequency of 100 Hz, which proved to be sufficiently low to avoid significant heating of the diode up to current densities of $15,000 \text{ A/cm}^2$. For farfield measurement the diodes were attached to a copper heat sink in the vacuum space of a dewar containing liquid nitrogen.

4. RESULTS

(a) *Threshold as a function of angle θ*

Figure 4 shows the measured threshold current densities at 77°K as a function of the angle θ for diodes with a length of $280 \pm 20 \mu\text{m}$ together with the calculated curve as derived in Section 2, normalized to the lowest thresholds at $\theta = 0^\circ$ (1000 A/cm^2) obtained from a large number of diodes made separately under similar conditions as the oblique diodes from the same starting material. This is reasonable, because the theory is based on ideal diodes and is therefore expected to give the lower limit for the experimental threshold. As the threshold current density is roughly proportional

^{*} This material was kindly supplied by Dr. A. Steinemann and U. Zimmerli, Battelle Institute, Geneva, Switzerland.

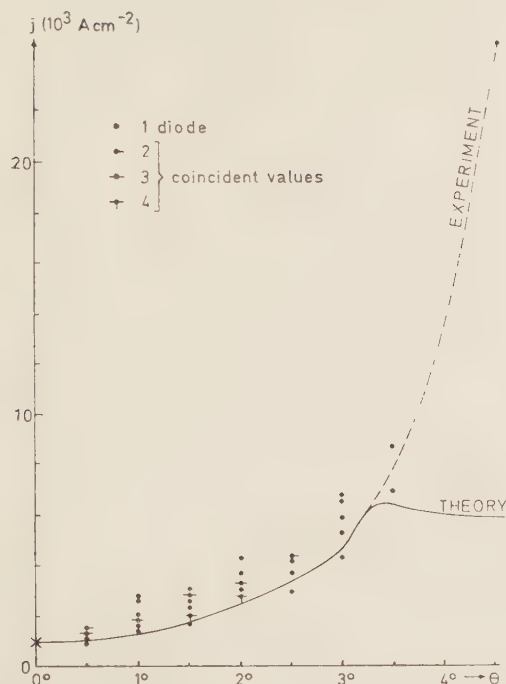


FIG. 4. Calculated and measured threshold current density as a function of θ at 77°K. The cross at 0° gives the lower limit of threshold for about 100 rectangular diodes.

to the reciprocal length of the diode, it is only possible to compare diodes of the same length. The cleaving procedure made it difficult to keep the length of the diodes constant. Therefore threshold values measured on diodes with lengths from 200 to 360 μm were reduced to values corresponding to a diode length of 280 μm .

As Fig. 4 shows, the threshold rises slowly at small angles, the starting-value at 0° being doubled at about 1.5°. For angles greater than 2.5° the threshold starts to rise more rapidly and reaches eight times the initial value near 3.5°.

Measurements at 4.2° and at 195°K (the latter by cooling with dry ice) show qualitatively similar results* (apart from a normalizing factor) as shown in Fig. 5. Therefore in the following only the measurements at 77°K, for which the most extensive data are available, are discussed.

* The measurements at 4.2° were kindly executed by R. Proebsting at the University of Wisconsin, Madison, U.S.A.

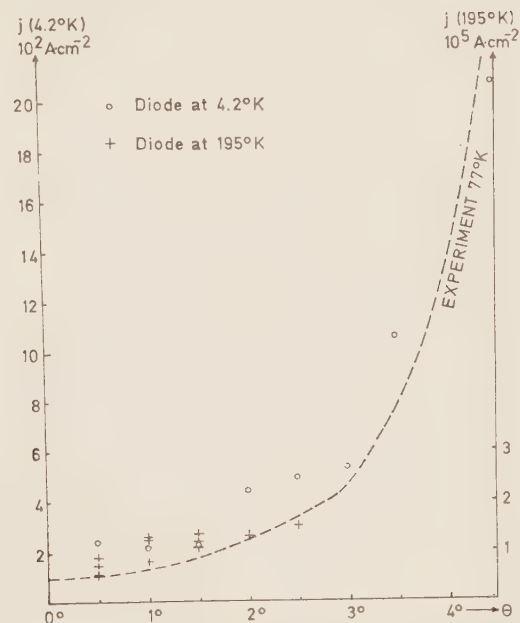


FIG. 5. Threshold current density as a function of θ at 4.2°K and 195°K. The experimental curve of Fig. 4 for 77°K is included for comparison. The scale factors for the data at 4.2°K were chosen to give the same intercept at $\theta = 0^\circ$.

(b) Far-field pattern

The far-field intensity distribution in a plane perpendicular to the junction plane, i.e. in the x -direction of the x - y plane of Fig. 1, should indicate the presence of off-axis modes. A purely axial mode would give a single peak with a nearly symmetric intensity distribution about an axis in the x - z plane, but displaced from the z -direction by refraction at the angled surface. However, in order to identify the number and the position of the far-field maxima it was first necessary to eliminate interference fringes caused by diffracted light from the opposite mirror as previously reported.⁽⁸⁾ This was achieved by roughening the n -type surface of the front mirror to within a few microns of the junction with a wire saw. The undisturbed farfields achieved in this way show for all our diodes only one maximum along the x -direction.

Figure 6 shows the direction of the far-field maximum as a function of the diode angle. Line (a) corresponds to the refracted axial beam. Lines (b)

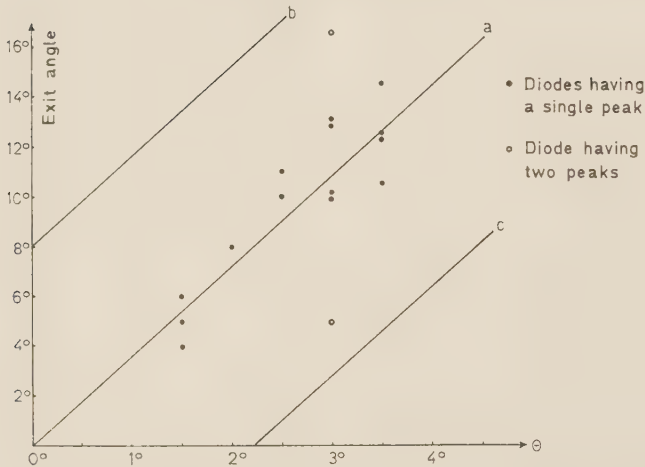


FIG. 6. Angular position of the main peak in the far-field pattern (with respect to the normal to the front) mirror as a function of angle θ . Line (a) corresponds to the refracted axial beam. Lines (b) and (c) correspond to the two lobes of a possible first order off-axis mode.

and (c) correspond to the angles which one would expect for the two lobes of the first off-axis mode, based on the calculations of STERN⁽¹⁾ and including refraction. It will be noted that all points lie much closer to the axial beam line (a) than to the lines for the first off-axis mode. All diodes showed only one intensity maximum in this plane demonstrating the absence of off-axis modes. One diode which indicated two maxima at $\pm 6^\circ$ from the axial beam was later found to have a cleavage step coincident with the junction plane.

5. DISCUSSION

(a) Threshold current vs. diode angle: comparison of experiment with theory

As shown in Fig. 4, the agreement between theory and the measured values is good up to angles of $\theta = 3.5^\circ$. As mentioned in Section 4 it is reasonable to expect the lower rather than the mean of the experimental values at each angle, to lie on the theoretical curve. That this is generally the case indicates that the calculated value of the internal electric field distribution is fairly accurate.

Above $\theta = 3.5^\circ$ there is a rapid divergence between experiment and theory. To account for this it is first important to note that the theory cannot be expected to apply for large angles. The effective reflection coefficient was calculated

on the basis of the field distribution at intrinsic threshold. After reflection at a tilted mirror, the initial distribution for the next reflection differs more and more from that at intrinsic threshold with increasing angle. Also the shape of the reflected beam near the first minimum and the second maximum depends critically on the relative values of the dielectric constant across the junction. Since these values are not known with great accuracy, the angle of 3.5° , corresponding roughly to the position of the first minimum of the reflected beam, may be regarded as an upper limit to which the theory can be applied.

Experimentally the behaviour of the diodes changed considerably at 3.5° and above. It became difficult to observe laser action; the spectrum in many cases showed only incoherent stimulated emission (superradiance). At 4.5° only a single diode showed a faint laser action, giving a lower limit of threshold for this angle. Figure 7(a) shows a typical spectrum of a normal diode, slightly above threshold, in comparison with that from a 3.5° diode, Fig. 7(b). It will be seen that the lines in the latter are broader and are more comparable to the spectrum of a diode below threshold emitting superradiantly, Fig. 7(c). This behaviour is to be expected from the very low effective reflectivity of the cavity. The correspondingly

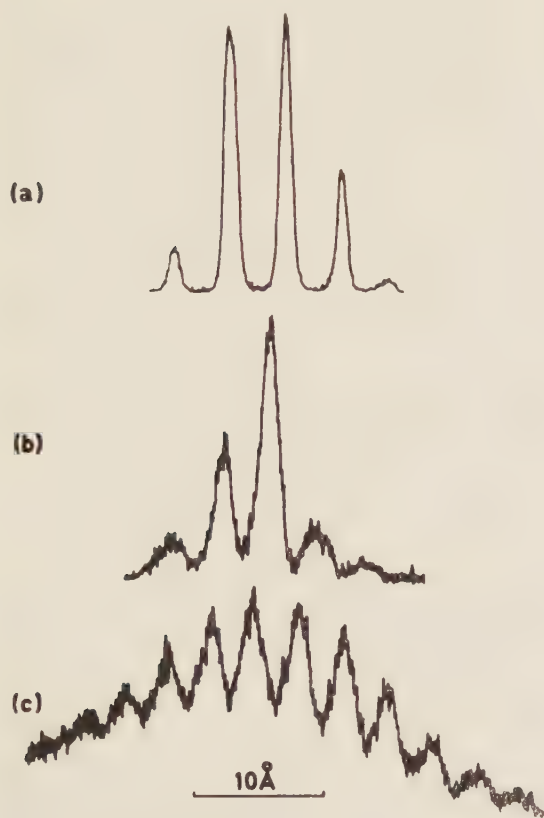


FIG. 7. Spectra of diode lasers (77°K). (a) Normal diode ($\theta = 0^\circ$) slightly above threshold, $j = 1200 \text{ A/cm}^2$; (b) Diode with $\theta = 3.5^\circ$ slightly above threshold, $j = 10,500 \text{ A/cm}^2$; (c) Superradiant diode $j = 5000 \text{ A/cm}^2$.

high gain necessary to cause oscillation leads to a large fraction of the output being in the form of superradiance. This is supported by measurements of the output intensity radiated into a small solid angle as a function of current, shown in Fig. 8 for two 3.5° diodes below threshold. At current densities greater than about 3000 A/cm^2 the output changes from a linear dependence on current to a quadratic dependence indicating the dominance of superradiance.^(9,10) Therefore at 8000 A/cm^2 , the threshold for 3.5° diodes, and above, the superradiant output is very considerable and may be expected to reduce the population inversion and hence the gain, making it increasingly difficult to raise the gain to threshold value as the angle is increased.

The gain necessary to reach threshold at 3.5° is given by the expression in brackets in equation (1). Substituting the values $R_0 R' = 0.03\%$, $\alpha = 10 \text{ cm}^{-1}$ and $L = 3 \times 10^{-2} \text{ cm}$ yields $g = 280 \text{ cm}^{-1}$ or an amplification factor of 4460 for one pass through the diode. This figure may be compared with the maximum gain of 2000 measured by CROWE and AHEARN⁽¹¹⁾ for a diode of similar length, suggesting that it is close to an upper limit.

(b) Application of results to other materials

The calculations of the reflected angular light distribution can be applied to determine the necessary accuracy of orientation for other materials. In general the required parameters are

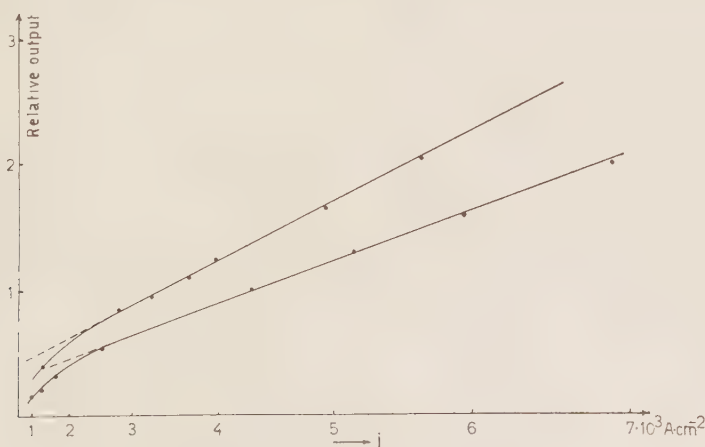


FIG. 8. Output power vs. current density (quadratic scale) for two 3.5° diodes below threshold.

not known to sufficient accuracy to permit this detailed calculation. However the approximate width of the reflected beam may be found by simple diffraction theory, identifying the beam width with that of the central maximum.

The dominant factor responsible for the decrease with θ of the reflected intensity in the direction of the active region is the exponent in equation (2) modified by equation (3).

$$k_0 n \sin \phi \cdot x. \quad (8)$$

For simplicity one may reduce the problem to the case of diffraction at a homogeneously illuminated slit of width $2w$. Then the position (ϕ_0) of the first minimum of the intensity distribution $I(\phi)$ is obtained from,

$$nk_0 \sin \phi_0 \cdot w \simeq \frac{2\pi n w \phi_0}{\lambda} = \pi \quad (9)$$

or

$$\phi_0 = \frac{\lambda}{2nw}. \quad (9a)$$

The position of the minimum is an upper limit for θ to prevent a significant increase in threshold current. When the values of λ , n and w are known, $\theta_{\max} = \phi_0/2$ may be calculated directly. The value for GaAs with $\lambda = 0.84 \mu\text{m}$, $n = 3.6$, $2w = 2 \mu\text{m}^*$ is $\theta_{\max} = 3.3^\circ$. This is in good agreement with the beamwidth corresponding to Fig. 2 and justifies the above simplified procedure. For InAs with $\lambda = 3.2 \mu\text{m}$, $n = 3.4$, $2w = 4 \mu\text{m}^{(12)}$ we obtain $\theta_{\max} = 7^\circ$, showing that in this case the orientation is less critical than for GaAs.

The most uncertain parameter is $2w$, it depends significantly on the junction fabrication process and is indicated by very few authors. The width (t) of the region with a negative absorption coefficient must be smaller than the diffusion length of electrons. However the width $2w$ of the radiation inside the laser is greater than t due to the waveguide properties of the material and in practice is generally of the same order of magnitude as the diffusion length (L),⁽¹⁾ namely,

$$2w \simeq L = \sqrt{(D\tau)} = \sqrt{\left(\frac{\mu k T}{e}\right)\tau} \quad (10)$$

* See Appendix.

where D is the diffusion constant, τ the lifetime of the carriers, e the elementary charge, k Boltzmann's constant T the absolute temperature and μ the mobility of the minority carriers. This estimate requires a knowledge of τ and μ .

When $2w$ cannot be determined it is possible to make a direct estimate of the width of the reflected beam inside the diode from the width of the far-field, since they are related by the refractive index, as shown in equation (3). For example some diodes made here from $\text{GaAs}_{0.75}\text{P}_{0.25}$ show an anomalous far-field beamwidth at $1/2$ intensity of only 2° , leading to an internal beamwidth of 0.6° . Diodes made from $\text{GaAs}_{1-x}\text{P}_x$, showing this behaviour, would have to be oriented therefore to within a fraction of a degree.

(c) Comparison of far-field patterns with predictions of geometrical optics

It is relevant to comment here on the geometrical optics treatment of diode laser modes. Axial beams as well as beams with multiple reflections at the boundary between the active region and the p - and n -side, often used as a model for off-axis modes,^(13,14) do not yield closed paths for oblique diodes, but leave the active region after a small number of passes, even for very small θ . The only exception which leads to a closed path is shown in Fig. 9. Here the

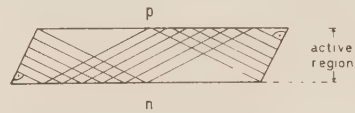


FIG. 9. Possible geometry of off-axis rays leading to closed paths in oblique diodes.

beam should leave the cavity in a direction perpendicular to the mirror. This kind of mode was never found experimentally, indicating that geometrical optics is insufficient to describe the conditions in the cavity of a diode laser.

(d) Polarization

As it has been shown by HATZ,⁽¹⁵⁾ GaAs diodes with a homogeneous nearfield show a preference for the TM mode, whereas our diodes which emit in filaments favour nearly always the TE mode.⁽¹⁶⁾ This last statement holds only for

normal rectangular diodes. In contrast our oblique diodes prepared in the same way show all possible angles between TE and TM modes, without any relation to the angle θ . It appears that the weak preference of the TE-polarization for diodes which emit in filaments is further diminished by the tilted mirrors.

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APPENDIX

Details of calculation of the internal electric field distribution

HATZ and MOHN⁽⁶⁾ have calculated the field amplitude distribution $u(x)$ [equation (2)] across the active region normal to the junction at intrinsic threshold. Using their notation, the u -function for the TE-mode, and for a set of material-parameters appropriate to the above diodes has the following forms for the different regions of η ,

$$\begin{aligned}
 u(x) &= \exp[(\eta - 1)(-1.26 + 0.797i)] & \text{for} & \quad 1 < \eta < \infty \\
 u(x) &= 1.514 + 0.231\eta - 0.746\eta^2 \\
 &\quad - 0.371i - 0.058i\eta + 0.428i\eta^2 & \text{for} & \quad 0.1 < \eta < 1 \\
 u(x) &= 1.512 + 0.24\eta - 0.792\eta^2 \\
 &\quad - 0.373i - 0.019i\eta + 0.235i\eta^2 & \text{for} & \quad -1 < \eta < 0.1 \\
 u(x) &= 0.495 \exp[(\eta + 1)(3.78 - 0.22i) - 6.07i] & \text{for} & \quad -\infty < \eta < -1.
 \end{aligned} \tag{11}$$

Here η is equal to x/w , and $2w$ is the width of the active region. Inside the active region ($-1 < \eta < +1$) u is approximated by quadratic polynomials and in the n - and p -region by exponential functions. From the distribution $u(x)$ we obtain the angular distribution $U(\phi)$ of the reflected light by means of equations (2) and (3). As the u -function is given in a simple analytic form, it was possible to integrate equation (2) in each region in a closed form. With $\sin \phi \simeq \phi$; $n = 3.6$; $\lambda = 0.84 \mu\text{m}$; $2w = 2 \mu\text{m}$ we obtain,

$$\begin{aligned}
 U(\phi) &= \left(\frac{-0.018 + 0.020i}{27\phi} + \frac{0.386 - 0.092i}{(27\phi)^3} \right) \exp(2.7i\phi) \\
 &+ \left(\frac{-1}{-1.26 + 0.797i + 27i\phi} + \frac{-0.002 - 1.00i}{27\phi} + \frac{-1.261 + 0.798i}{(27\phi)^2} \right. \\
 &\quad \left. + \frac{-0.856 - 1.492i}{(27\phi)^3} \right) \exp(27i\phi)
 \end{aligned} \tag{12}$$

$$\begin{aligned}
 & + \left(\frac{0.48 - 0.118i}{3.78 - 0.022i + 27i\phi} + \frac{0.118 + 0.481i}{27\phi} + \frac{-1.824 + 0.489i}{(27\phi)^2} \right. \\
 & \left. + \frac{0.47 + 1.584i}{(27\phi)^3} \right) \exp(-27i\phi).
 \end{aligned}$$

This expression appears to diverge for $\phi = 0$. A more detailed investigation shows however, that for small values of ϕ the terms with negative exponents cancel. Nevertheless, for $\phi = 0$, a more accurate value for U is obtained by introducing $\exp(ik\phi x)|_{\phi=0} = 1$ into equation (2) before carrying out the integration, yielding,

$$U(0) = 1.226 - 0.224i$$

The final evaluation of UU^* was carried out on a computer, giving the curve of Fig. 2. The knee in the curve of Fig. 4 at 3° was found to be quite dependent on the value of $2w$. A value of $2w = 2\mu\text{m}$ was chosen to give the best fit with the experimental results.

Observation of Mode Coupling in GaAs Lasers

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In the course of extended investigations of the nearfield and farfield of GaAs laser diodes we found a particularly interesting case which will be reported on here.

The diodes investigated were made from a starting material containing several 10^4 dislocations per cm^2 . The nearfield of these diodes is highly inhomogeneous, that is, the laser emission takes place in terms of 'spots'. The investigation of polarization and spectrum indicates that each spot is caused by an independently oscillating filament in the active zone. The polarization of the emitted laser light is almost always TE (E-vector in the plane of the $p-n$ junction) [1].

A particular diode showed one spot at threshold, one more with slightly higher current, and finally 3 spots with still higher current. The measured distance between adjacent spots was $11\ \mu\text{m}$. The spectrum of the three spots looked like that of a single spot, that is it showed a single set of longitudinal modes. The polarization was TE. There are three possibilities to account for a relation between the three spots:

- a) the three filaments oscillate independently,
- b) the three spots should be identified as intensity maxima of a higher order off-axial mode,
- c) the three filaments oscillate in a coupled way with a fixed phase relation.

A distinction between these cases is aided by the farfield.

In the first case the intensities of the diffraction patterns of the individual spots would add, that is one would obtain the farfield characteristic of a single spot with a maximum at 0° . The experiment, on the other hand, showed two approximately equal main maxima at $\pm 1.8^\circ$ and a minimum at 0° . Thus the first case may safely be excluded.

The farfield does not permit a distinction between the second and third cases. The second case may be excluded, however, for the following reasons:

The position of the first (and second) spot is not altered with the appearance of the second (third) one. The position of one or more intensity maxima, on the other hand, is not preserved when the oscillation changes from the lowest order to higher transverse modes [2]. In addition it is unlikely that a clear cut higher transverse mode could exist in this highly inhomogeneous material. This inhomogeneity is evidenced by the fact that these diodes never emit in terms of a homogeneous ribbon in the nearfield as do diodes made from dislocation free material. Similarly the intensity distribution of the three spots in the nearfield shows no resemblance to the Hermite-Gauss distribution one should expect for a higher order mode.



Figure 1
Picture of the farfield
from 3 coupled spots.

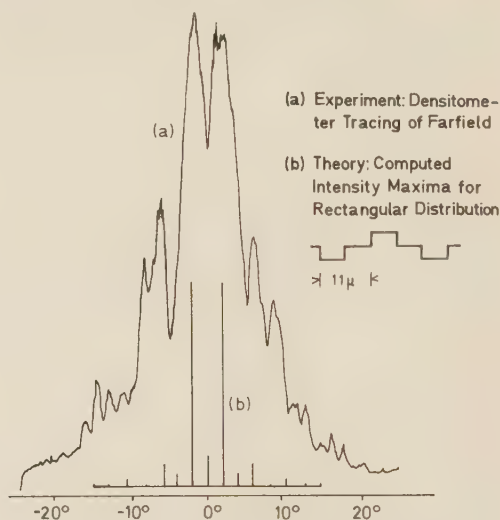


Figure 2
Comparison between experimental and
computed farfields.

To shed additional light on the problem of mode coupling we computed the farfield that would result from a 'rectangular' field distribution for each of the spots and a phase difference of 180° between adjacent spots. The distance between the spots was taken from a photograph of the nearfield. As seen in Figure 2, there is a satisfactory agreement between this computation and the experiment as far as the position of the intensity maxima is concerned. The observed sidelobes, however, are appreciably higher than the computed ones. This seems to indicate that the assumption of constant phase and rectangular amplitude across each spot is not refined enough.

Mode coupling in lasers with plane parallel mirrors was treated before by BASOV [3]. From this theory one would conclude that mode coupling is likely to occur in our geometry, as it leads to a reduction of diffraction losses of about 7 per cent when compared to the uncoupled case. According to this theory the 180° phase difference comes about because the first diffraction side lobe of the radiation reflected from one of the laser mirrors comes to lie on a mirror of the adjacent laser.

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Curriculum vitae

Ich wurde am 26. Mai 1938 in Binningen (BL) geboren als Sohn des Emil Friedrich Deutsch und der Theodora Magdalena, geb. Jung. Die ersten vier Jahre der Primarschule absolvierte ich in Chur, die restlichen zwei sowie zwei Jahre Sekundarschule in Zürich. Im Jahre 1953 trat ich in die Kantonale Oberrealschule in Zürich ein, welche ich im Herbst 1957 mit der Maturität C abschloss. Hierauf entschloss ich mich zum Studium der Physik an der Abteilung IX der ETH mit Hauptrichtung Experimentalphysik. Nach Ausführung einer Diplomarbeit über γ - γ -Richtungskorrelation erwarb ich im Herbst 1961 das Diplom als Physiker. Von November 1961 bis Juli 1964 arbeitete ich im Physikalischen Laboratorium der Firma Brown, Boveri & Co in Baden auf dem Gebiet der Halbleiter. Im August 1964 trat ich eine Stelle als Assistent im Institut für angewandte Physik der Universität Bern an und erhielt dadurch die Möglichkeit, meine Studien an der philosophisch - naturwissenschaftlichen Fakultät zu vervollständigen. Meine Tätigkeit umfasste Grundlagenforschung und Entwicklungsarbeiten an Halbleiterlasern und führte zu der vorliegenden Dissertation.

